ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP19

EXPERIMENTAL INVESTIGATIONS ON THE HIGH-INTENSITY EFFECTS NEAR THE HALF-INTEGER RESONANCE IN THE PSB

T. Prebibaj*, F. Antoniou, F. Asvesta, H. Bartosik, CERN, Geneva, Switzerland
G. Franchetti, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Abstract

Space charge effects are the main limitation for the brightness performance of the Proton Synchrotron Booster (PSB) at CERN. Following the upgrades of the LHC Injectors Upgrade (LIU) project, the PSB delivered unprecedented brightness even exceeding the projected target parameters. A possibility for further increasing the brightness is to operate above the half-integer resonance $2Q_y = 9$ in order to avoid emittance blow-up from resonances at $Q_{x,y} = 4$ due to the strong space charge detuning. The half-integer resonance can be compensated to a great extent using the available quadrupole correctors in the PSB, and also deliberately excited in a controlled way. The control of the half-integer resonance and the flexibility of the PSB to create a variety of different beam and machine conditions allowed the experimental characterization of space charge effects near this resonance. This contribution reports the experimental observations of the particle trapping during the dynamic crossing of the half-integer resonance, as well as systematic studies of the beam degradation from space charge induced resonance crossing.

INTRODUCTION

The brightness performance of the PSB is limited by space charge effects at injection. At high beam intensities, emittance growth is induced by the interaction of the beam with the resonances around the integer tunes $Q_{x,y} = 4.0$ due to the large space charge tune spread. Studies demonstrated that operation with high working points at injection, i.e. $4.40 < Q_{x,y} < 4.5$, far from $Q_{x,y} = 4.0$, mitigate this emittance growth and increase the beam brightness [1]. An injection at even higher working points, i.e. above the half-integer resonance $2Q_y = 9$ ($Q_y > 4.5$), could further mitigate the undesired emittance growth. However, in this scenario, to reach the extraction working point $(Q_x, Q_y) = (4.17, 4.23)$, the half-integer resonance needs to be dynamically crossed during the acceleration cycle. The dynamic crossing of (compensated) third and fourth order resonances is a common practice during the PSB operation [2]. However, the half-integer resonance is much stronger and thus more difficult to control to avoid particle losses and/or emittance growth.

In this context, a series of studies were initiated in order to characterize the effects of space charge when crossing the half-integer resonance with tunes $Q_y > 4.5$ (from above). These effects can change depending on the resonance strength, the crossing speed and the space charge tune spread. The eventual goal is to experimentally study and understand the beam behaviour under these conditions and to find ways to increase the achievable beam brightness.

Operationally, the high-brightness beams in the PSB have space charge tune spreads that can exceed $\Delta Q_{x,y} = -0.5$ and thus overlap multiple resonances. In addition, the synchrotron oscillations induce a modulation in the local line density of the particles and therefore a modulation in their space charge tune-shift, which can lead to periodic resonance crossing and associated beam degradation [3]. To remove some of the operational complexities, the starting point of the studies presented here was the use of a relatively lower intensity, unbunched (coasting) beam in a non-accelerating cycle. This contribution will focus only on the half-integer crossing under these special beam conditions.

EXPERIMENTAL SETUP

The half-integer resonance $2Q_y = 9$ has been characterized experimentally in the PSB [4]. In the bare machine, the resonance is excited by residual quadrupole errors in the machine and can be compensated by two families of orthogonal quadrupole correctors, namely QNO412 and QNO816. A controlled excitation of the resonance can be performed by slightly varying the strengths of the correctors with respect to their compensating value. In this way, the resonance stopband has a finite width that is strong enough to have a measurable effect on the beam, but not too strong (like the uncompensated resonance) so that the beam is fully lost and cannot be measured. For the purposes of these experiments the half-integer resonance is excited by changing the current of the QNO816 family by $\delta I_{816} = -2$ A from its compensation value (integrated focusing strength of $\delta k_1 l_{816} = -6.2 \times 10^{-4}$ m^{-1}). This corresponds to a stopband width of smaller than $\delta Q = 0.004$ [4].

Beams with different intensities and transverse emittances can be used in the PSB. The coasting beam is created by injecting a long pulse from Linac4, that almost fills the PSB circumference, and keeping all RF cavities switched off. The beam fully debunches after only 500 turns. In addition, the vertical chromaticity has been corrected close to zero using the available sextupole correctors. Therefore, the chromatic tune spread can be considered negligible.

PARTICLE TRAPPING

The stability of the particle motion near a resonance depends on the distance of the working point from the resonance and the amplitude detuning. Here, the detuning of the particles comes mainly from the space charge defocusing which is amplitude dependent: particles at low amplitude (near the beam core) receive the strongest detuning while

* tirsi.prebibaj@cern.ch

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP19

particles at higher amplitudes (near the beam tails) receive smaller detuning, resulting in a tune spread. The tune spread remains stationary over time since there is no synchrotron motion (coasting beam). The presence of the amplitude detuning creates stable resonance islands in the phase space trajectories of the particles. The order of the resonance, here second order, determines the number of the islands, their position depends on the distance of the bare tune from its value at the resonance ($Q_y = 4.5$) and their size on the resonance strength and the detuning gradient [3].

A crossing of the half-integer resonance was performed experimentally in the PSB. The resonance was dynamically crossed from above ($Q_y > 4.5$) by changing the vertical tune and keeping the horizontal tune constant ($Q_x = 4.15$), as shown in the tune diagram of the left plot of Fig. 1. A coasting beam of an intensity of $N_b \approx 40 \times 10^{10}$ p$^+$, $\epsilon_x \approx 1.5$ μm, $\epsilon_y \approx 1.0$ μm, $(\delta p/p)_{\mathrm{RMS}} \approx 1.4 \times 10^{-3}$ was used. The analytical estimation of the tune spread [5] is shown with the orange polygons and is approximately $\delta Q_y^{SC} \approx -0.05$, which is more than 10 times larger than the width of the stopband. The vertical tune as a function of time is shown in the right plot of Figure 1. At the injection energy of the PSB, one millisecond corresponds to approximately 1000 revolutions around the ring. Thus, the tune change per turn (crossing speed) is approximately $\delta Q_y/\mathrm{turn} = 0.65 \times 10^{-6}$.

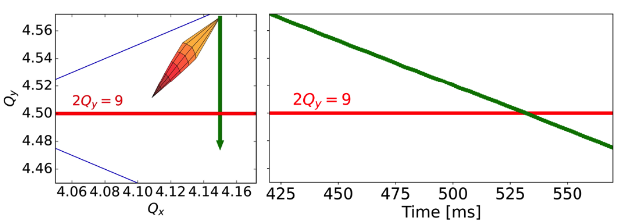

Figure 1: Left: working point evolution (green arrow) and estimated space charge tune spread (orange polygons). Right: measured vertical tune as a function of time during the dynamic crossing of the half-integer resonance $2Q_y = 9$.

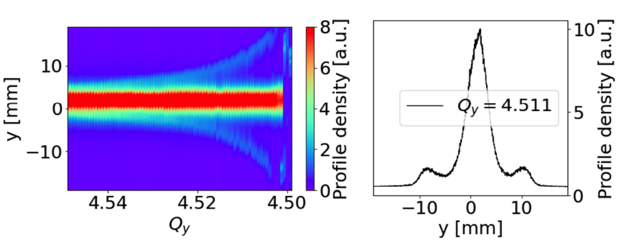

Figure 2: Left: evolution of the measured vertical beam profile as a function of the vertical tune when dynamically crossing the $2Q_y = 9$ resonance. Right: measured vertical profile at $Q_y = 4.511$.

The particle trapping during the half-integer resonance crossing was observed through the vertical beam profiles. The vertical profiles were measured every millisecond using a wire scanner [6] and are shown in the left graph of Fig. 2. In this graph, the horizontal axis corresponds to the measured tune, the vertical axis to the y-position and the color to the density of the profile measurements in arbitrary units. The graph shows about 150 measured beam profiles, where each profile measurement comes from a different PSB cycle with the same beam and machine configurations (similar beam intensities, emittances, crossing speed, chromaticity correction). It should be noted that although the reproducibility of the PSB is excellent, there are always some fluctuations in the injection efficiency and the beam intensity. For $Q_y > 4.54$, the beam is far from the resonance and the profiles follow a near Gaussian distribution. While the beam moves closer to the half-integer resonance, particles from the beam core (that have the stronger detuning) reach the $2Q_y = 9$ resonance and two stable islands appear in the vertical phase space trapping particles. As the tune ramp continues ($Q_y < 4.53$), the resonance islands move slowly to larger amplitudes, along with the particles that have been trapped. As shown in the right graph of Fig. 2, at which $Q_y = 4.511$, the trapped particles appear as two beamlets in the measured profiles. The space charge forces gradually become weaker and the tune shift decreases slightly (the beam core density is still similar to the initial beam conditions). While the beam continues to approach the half-integer resonance, the islands continue to move outwards until particles hit the machine aperture and are lost ($Q_y \approx 4.503$). Shortly after, the beam core is lost as well. Investigations using macroparticle simulations are presently ongoing to better understand why the beam core is lost shortly after the two beamlets hit the machine aperture.

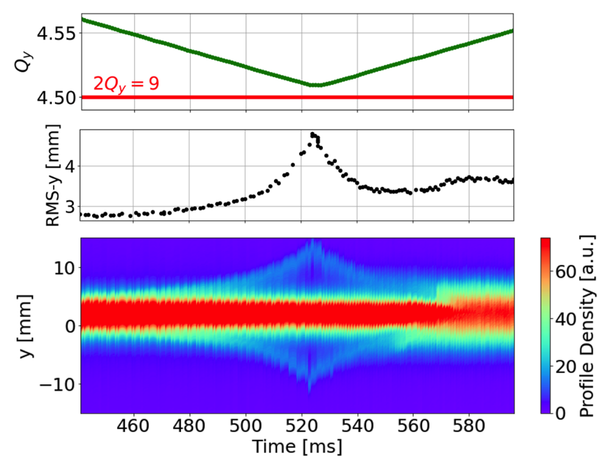

Figure 3: Vertical tune (top), RMS vertical beam size (middle) and measured vertical beam profiles (bottom) vs. time.

To further study the process of trapping in the half-integer, a similar experiment was performed. With the same beam parameters, the half-integer resonance was again adiabatically approached but this time, just before entering the stopband, the tune was moved away from the resonance. The tune change over time is shown in the top graph of Fig. 3. The vertical beam profiles, measured again every millisecond over multiple identical cycles of the PSB, are shown in the bottom graph of Figure 3 and their RMS beam size in the middle graph. In the first part of the tune ramp ($t < 530$ ms) the

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP19

islands, along with the trapped particles, move towards larger amplitudes. After the tune ramp changes slope ($t > 530$ ms), the islands move inwards, towards the beam core, and become smaller. Thus, particles cross the separatrix of the resonance islands and fill the phase space around the beam core, leading to filamentation. Due to this process, which takes place between $t = 560$ ms and $t = 580$ ms, the initial particle distribution cannot be restored. The collapse of the islands to the center results in a distribution with an RMS beam size approximately 1 mm larger compared to the initial value.

CHANGING THE CROSSING SPEED

The effect of the half-integer resonance on the beam depends on the resonance crossing speed. This was studied both experimentally and in simulations. The experiment consisted of a coasting beam that had a space charge detuning of approximately $\delta Q_y^{SC} \approx -0.03$ (40 % smaller than previously). Using this beam, the half-integer resonance (with the controlled excitation) was crossed completely with different crossing speeds ranging from $\delta Q_y/\mathrm{turn} \approx 2 \times 10^{-6}$ to $\delta Q_y/\mathrm{turn} \approx 50 \times 10^{-6}$. The beam intensity and emittance was measured before the tune ramp started and after it finished. Figure 4 shows the resulting emittance growth (blue crosses) and intensity loss (red crosses) as a function of the crossing speed. For a slow (adiabatic) crossing ($\delta Q_y/\mathrm{turn} < 60 \times 10^{-6}$), like in the scenario discussed previously, the probability of particles getting trapped in the moving islands is high [7]. Therefore, the islands are populated with particles that get carried outwards until they hit the machine aperture. This results to beam losses up to 25 % and an emittance reduction. Note that in this case, in which only the space charge tune spread is weaker, the beam core survives the resonance crossing for all crossing speeds.

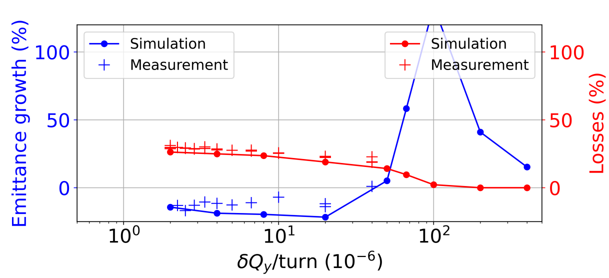

Figure 4: Crossing the half-integer resonance with a coasting beam and different crossing speeds. Emittance growth (blue) and beam losses (red) as a function of the crossing speed for a fixed space charge strength. Experimental data shown with crosses and simulations with dots.

This experiment was reproduced in tracking simulations using the PyOrbit code [8] which implements a Particle-In-Cell algorithm for the space charge calculations. The simulation results are shown with the dots in Fig. 4 and are in excellent agreement both qualitatively and quantitatively with the measurements. If the crossing speed is relatively fast (non-adiabatic), the moving islands still capture particles but now there is a high probability that they will cross the separatrix and get unlocked from the resonance. This process results in an emittance growth, due to filamentation, without considerable losses. In the graph, these cases correspond to crossing speeds higher than the critical speed of $\delta Q_y/\mathrm{turn} \approx 60 \times 10^{-6}$. For even faster crossings ($\delta Q_y/\mathrm{turn} > 100 \times 10^{-6}$), the emittance growth decreases towards zero. Unfortunately, tune changes faster than $\delta Q_y/\mathrm{turn} \approx 50 \times 10^{-6}$ are too aggressive for the power converters of the PSB quadrupoles and cannot be achieved experimentally. Therefore, for this configuration, the non-adiabatic region cannot be reached experimentally.

The critical speed between the adiabatic and non-adiabatic resonance crossing depends on the size of the resonance islands. For larger islands, the critical speed at which the crossing becomes non-adiabatic is higher. The size of the island itself depends the resonance strength and the space charge detuning gradient. For the operational case of the PSB, at which the half-integer resonance will be compensated to a very good extend and the detuning gradient will be much stronger (higher beam intensity), the critical speed is expected to be much lower than $\delta Q_y/\mathrm{turn} \approx 60 \times 10^{-6}$ and so no trapping should occur. Nevertheless, the operational beams are bunched and thus the effects of the periodic resonance crossing are expected to dominate. This will be the subject of future studies.

CONCLUSIONS AND OUTLOOK

In this contribution, the half-integer resonance $2Q_y = 9$ was crossed from above with a coasting beam under relatively strong space charge. The evolution of the particle trapping in the half-integer resonance islands was experimentally characterized for the first time under a set of precisely controlled beam and machine conditions. Systematic measurements were performed with different crossing speeds and the macroscopic effects on the beam in terms of emittance growth and beam losses were identified and compared to simulations, which agreed very well.

The characterization of the half-integer resonance effects could be of operational interest for the PSB. An injection above the half-integer resonance is expected to further mitigate the space charge induced emittance blow-up at low energy and possibly increase the brightness. Measurements with beams that are closer to the operational conditions of the PSB are currently ongoing.

ACKNOWLEDGEMENTS

The authors would like to thank S. Albright, G.P. Di Giovanni, T. Levens, F. Roncarolo and the PSB Operations team for their help and continuous support.

REFERENCES

[1] T. Prebibaj *et al.*, “Injection chicane beta-beating correction for enhancing the brightness of the CERN PSB beams”, in

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP19

Proc.HB'21, Batavia, Illinois, USA, Oct. 2021, pp. 112-117. doi:10.18429/JACoW-HB2021-MOP18

[2] F. Asvesta *et al.*, "Resonance Compensation for High Intensity and High Brightness Beams in the CERN PSB", in *Proc. HB'21*, Batavia, Illinois, USA, Oct. 2021, pp. 40-45. doi:10.18429/JACoW-HB2021-MOP06

[3] G. Franchetti and I. Hofmann, "Modeling of Space Charge Induced Resonance Loss", *AIP Conf. Proc.* vol. 642, pp. 260-262, 2002.

[4] T. Prebibaj, F. Antoniou, F. Asvesta, H. Bartosik, and G. Franchetti, "Studies on the Vertical Half-Integer Resonance in the CERN PS Booster", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 222–225. doi:10.18429/JACoW-IPAC2022-MOPOST058

[5] F. Asvesta and H. Bartosik, "Resonance Driving Terms From Space Charge Potential", CERN, Geneva, Switzerland, CERN-ACC-NOTE-2019-0046, Oct. 2019, https://cds.cern.ch/record/2696190/.

[6] R. Veness *et al.*, "Installation and Test of Pre-series Wire Scanners for the LHC Injector Upgrade Project at CERN"in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 412-414. doi:10.18429/JACoW-IPAC2017-MOPAB121

[7] G. Franchetti and I. Hofmann, "Particle Trapping by Nonlinear Resonances and Space Charge, in *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 561, no. 2, pp. 195-202, June 2006. doi:10.1016/j.nima.2006.01.031

[8] PyORBIT collaboration, https://github.com/PyORBIT-Collaboration/.